New system should make runways safer

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Abstract:
WASHINGTON (AP) -- A ground safety system to help prevent runway collisions will be provided to 25 airports across the country, including Bradley International Airport in Connecticut, the Federal Aviation Administration said yesterday. The new system, called ASDE- X is designed to give air traffic controllers information about the location of planes and vehicles at night and in bad weather when visibility is limited.

Full Text:

WASHINGTON (AP) -- A ground safety system to help prevent runway collisions will be provided to 25 airports across the country, including Bradley International Airport in Connecticut, the Federal Aviation Administration said yesterday. The new system, called ASDE- X is designed to give air traffic controllers information about the **location** of planes and **vehicles** at night and in bad weather when visibility is limited. ASDE-X is similar to the ASDE-3 ground radar now providing similar data to controllers at the nation's 34 busiest airports. The new units will provide added protection to 25 smaller, less busy fields, the agency said. The airports that will get ASDE-X were selected through a safety **risk assessment** conducted by the FAA and Massachusetts Institute of Technology, which focused on potential accidents and fatalities. FAA Administrator Jane Garvey announced the decision to purchase the equipment at the opening of a three-day airport safety conference in Washington. The 34 busiest airports are scheduled to be upgraded by 2002 to a more complex system that will warn of potential collisions and inform controllers of the **locations** of aircraft and **vehicles**. Garvey said the FAA plans to award a contract for production of ASDE-X in September. The number and rate of close calls on runways increased during most of the last decade before dropping slightly last year. However, the number of incidents jumped 27 percent in the first five months of this year compared with the corresponding period in 1999.

Risk assessment and structural integrity aspects of materials behaviour

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[Headnote]

Risk has always been an inherent part of everyday life, but quantified assessment of risk is now an important part of several different aspects of materials and engineering applications. Risk is taken into account as an integral part of the design of many constructions in limit state design through the use of partial safety factors to achieve a target reliability, depending on the consequences of failure and the uncertainties of the input data and design relationships. Risk is also increasingly being used as a basis for decisions on inspection, maintenance, and life extension of engineering structures and infrastructure. As part of the effective management of projects, assessments of the financial risks both for the client and for the contractor are essential requirements. Environmental risk assessments are obligatory for major projects before decisions to proceed can be taken. The current status of the application of risk analysis methods to avoidance of failure by plastic collapse, fracture, buckling, fatigue, creep, and corrosion is reviewed, and applications in a range of industries are considered. The application of risk analysis to the use of new materials, methods of construction, and life extension is then briefly explored. Finally, the importance of a proper understanding of both risk analysis and materials behaviour for students on degree courses is stressed.

Sir Monty Finniston is probably best remembered as a major force in the British Steel Corporation and for the report of the committee he chaired into the future of the engineering profession, though he was also involved with many other companies and organisations.l Although much has changed since his time, his contributions were landmarks which laid down paths for future development with much success. Sir Monty's scientific and technical achievements were recognised by his election as a fellow of both the Royal Society and the Fellowship (now Royal Academy) of Engineering. He also served as President of the Metals Society and the Welding Institute and as Vice President of the Royal Society.

Sir Monty was deputy chairman of British Steel from 1967 to 1973, Chief Executive from 1971 to 1973, and Chairman from 1973 to 1976, during which time the company was a nationalised corporation under public ownership. It had become a sprawling assembly of many different works with poor efficiency and profitability. Under the leadership of Sir Charles Villiers, Sir Monty Finniston, and Sir Robert Scholey, British Steel was turned round so that its current successor, Corus, is one of the most efficient producers of high quality steel and aluminium in the world.

The Finniston report, as it became universally known, laid the foundations for abolishing the ineffective Council of Engineering Institutions and replacing it with the Engineering Council. However, the government of the day did not follow Sir Monty's recommendations in full, and the Engineering Council had a difficult birth and early life. Sir Monty had wanted the new council to provide leadership and to be a driving force in raising the status of the engineering

profession and in attracting the best possible quality of recruits for the future, however the relationship between the Engineering Council and the professional institutions has continued to be difficult. The increased emphasis on engineering applications in degree courses and in the training of engineers and the introduction of the MEng degree were both direct results of the recommendations in the Finniston report concerning the `formation of engineers'. These are now of course included in the Engineering Council's document SARTOR (`Standards and routes to registration').2 The reissue of this document, with the basic requirement for a four year MEng degree course as the main route to Chartered Engineer status, with 24 A level points as the entry requirement for 80% of the cohort, and a three year BEng degree with an entry requirement of 18 points leading to Incorporated Engineer status, is currently causing major changes in university level provision of training.

By the nature of his character and through the responsibilities he bore, Sir Monty was used to having to weigh up the information available and take decisions allowing for incomplete information and uncertainties. As such he had an inherent grasp of the concept of risk. He was always keen to learn and to take advantage of new technologies and new developments and would have been fascinated by the potential advantages of risk assessment, although he might well have been sceptical about accepting numerical results absolutely!

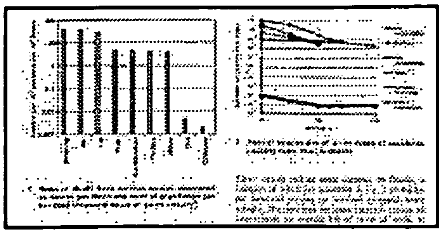
The nature of risk

A dictionary definition of risk is `the chance of loss or injury'. The general public has a basic perception of risk in connection with everyday activities, which is usually manifest as a perception of injury or death. Some figures for accidental deaths and injuries requiring hospital treatment in the UK for 1999 are given in Table 1. It can be seen that the number of deaths from road accidents is slightly less than the number of deaths from accidents in the home. If these figures are divided by the current total UK population of 59 million, the results give a probability of death per person per year of 533 x 10^sup -5^ for road accidents and 667 x 10^sup -5^ for accidents in the home. The table also shows that the number of persons injured in the home requiring hospital treatment is over 700 times the number of deaths and about 4-5 times the number of persons with sporting injuries requiring hospital treatment.

There have been two authoritative reports on risk published by the Royal Society, in 19833 and 1992.4

These reports include some statistics on deaths, a selection of which are presented in Fig. 1 as deaths per thousand persons per hundred thousand hours activity. The time base for these figures is chosen to approximate an average life of hours at work. It should be noted that the vertical scale in Fig. 1 is logarithmic. Expressed in this way, the risks of death from smoking and travel by air or car are approximately the same or somewhat greater than those from accidents on construction sites, in factories, or in the home. It can be seen that on this basis the risk of death from collapse of buildings is over four orders of magnitude lower than the highest level shown in Fig. 1. However great care is required in the interpretation of statistics in this field. It is not clear that the same time denominator of 105 hours activity is applicable to the different activities in this table. Transport statistics are often quoted as deaths per passenger mile or kilometre, although a more realistic format is considered by some to be deaths per passenger journey. In the scientific field risk has a more precise definition, as follows: risk is the product of the frequency of occurrence of a given adverse event and the consequences of the event occurring, which can also be interpreted as the product of the probability of occurrence of an adverse event and the consequences of the event. All Chartered Engineers are expected to have a basic understanding of the concepts of risk, and a guidance document to assist in this has been issued by the Engineering Council.5

Figure 2 shows another way of presenting this type of information. Here the frequency of events per year which cause more than N deaths is plotted against N itself for a number of common activities. The results for air, sea, and rail travel and for failure of dams are taken from actuarial figures. The figures for accidents involving nuclear reactors and public assemblies are based on modelling calculations. The difference between the group of the top four items in Fig. 2 and the two at the bottom is extremely significant. Clearly the general public is prepared to live with the level of risk involved in everyday activities such as travel, although any major accident leading to a significant number of deaths does cause great concern. Such accidents are usually investigated by a public inquiry which in turn leads to recommendations to try to ensure that similar events are avoided in future. Engineering activities are expected to work to a completely different level of risk than that which members of the public may be prepared to accept when they have a free choice. This raises the concept of `perception of risk', which has been addressed by the Health and Safety Executive (HSE) in discussion documents6-$ and by the Standing Committee on Structural Safety,9 and was the subject of this year's Royal Academy of Engineering Lloyd's Register Lecture.10



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1 Risks of death from various causes expressed as deaths per thousand head of population per hundred thousand hours of given activity3
2 Annual frequencies of given types of accidents causing more than N deaths

Table 1 Some figures for injuries in the UK in 1999 involving hospital visits

Incident	Annual frequency
Road death	3148
Home	
Death	3846
Fall	1 800 000
Collision	650 000
Burn	102 000
Accidental poisoning	41 000
All home incidents	2 800 000
Sports	
Football	438 000
Rugby	78 000
Roller skating	37 000
Cricket	22 000
Ice skating	18 000
Swimming	18 000
Hockey	15 000
Squash	9000
Tennis	6200
All sports injuries	520 000

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Table 7

Figure 3 shows proposals by the Nordic countries for acceptable target levels of risk for different types of engineering construction. It should be noted that on a plot of frequency/probability of occurrence versus consequences using logarithmic scales, constant risk is represented by a straight line, so that each category in the figure is a line of constant risk. This can be compared with the figures put forward by the HSE as a basis for the ALARP (`as low as reasonably practicable') principle shown in Fig.4,6 which suggests the following three main regions on a risk diagram: first, where the product of frequency F and consequences N is greater than 0' I per year the risk is unacceptable; second, the ALARP region is where 10-' >FN> 10-4; and third, where FN< 10-' the risk is negligible and acceptable. In the ALARP region it is required that control measures be taken to drive the residual risk towards the acceptable region. If society expects risk reductions, the residual risk in this region is only tolerable if such reductions are impracticable or require action grossly disproportionate to the reduction in risk achieved. Comparing Figs. 3 and 4 it can be seen that the Nordic countries' proposals are all in the acceptable region, with the exception of the risks relating to masts and offshore structures which fall at the bottom of the ALARP region.

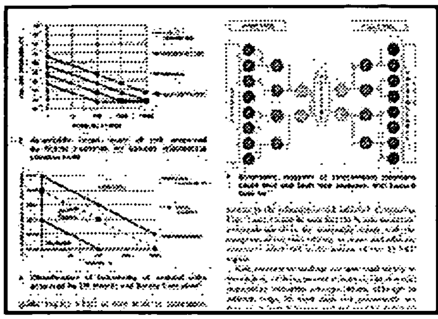
Risk assessment methods are now used widely in the nuclear, offshore, general structural, and chemical engineering industries amongst others, although in different ways. In most cases risk assessments are part of an overall picture and are used for guidance and ranking rather than for attempting to determine absolute values of risk. This is partly because of the lack of firm data or because the methods are relatively young in development. Often, risk assessment is carried out using event tree or fault tree analyses, as shown in Fig. 5 (the `hazard bow tie'), which enable logical tracing of all the factors leading to or from hazardous events.

Application of risk assessment methods to design

Limit state design

In the UK over the past twenty or so years there has been a major shift in the design of structures towards the use of limit state design. The basic concept is that a structure should be designed so that the probability of failure should not be greater than a target value allowing for uncertainties in the loading effects and for scatter or uncertainties in resistance effects including scatter in material properties. The previous approach to design, known as allowable stress design, had been that there should be a safety factor between the maximum stresses in the structure produced by the maximum expected loading and the material strength (usually yield strength in the UK). The major difference occurs with redundant structures where failure by plastic collapse requires the formation of a mechanism with a number of plastic hinges, and these hinges may develop at different loads. This means that the structure may

have a considerable reserve of strength above the condition when yielding first occurs, which would be the condition governing an allowable stress design.



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3 Acceptable target levels of risk proposed by Nordic countries for various engineering constructions
4 Classification of tolerability of societal risks proposed by UK Health and Safety Executives
5 Schematic diagram of relationship between event tree and fault tree analyses: the 'hazard bow tie'

Use of risk assessment methods in this way requires the estimation of the probability of failure. This is the basis of a whole subject area known as reliability analysis. In principle the determination of the probability of failure requires the solution of an equation which expresses the relationship between all the relevant variables which affect failure by a particular mode, including allowing for the uncertainties or scatter in these variables. The complete determination of this requires the solution of the convolution integral between expressions for the load and resistance effects in a failure equation. In practice it is rarely possible to carry this out when there are many variables involved. However, there are a number of approximate methods which can be used to produce good estimates of the probability of failure. The most popular of these are first order second moment methods and Monte Carlo simulations.

First order second moment methods involve estimation of the reliability index [3 through a numerical procedure applied to solve a failure equation for the particular mode of failure under consideration. This reliability index is uniquely related to the probability of failure when the distributions concerned are normal distributions. The easiest way to see the meaning of the reliability index is shown in Fig. 6 for the relationship between load effects and resistance effects when the distributions of both are normal. The failure margin M can be written in general terms as

$M = R - L$

where R is the expression for resistance effects and L is the expression for load effects. Both of these expressions may themselves involve several variables which in turn take the form of distributions. Failure occurs when the margin M is less than or equal to zero.

The reliability index β is given by

$\beta = (\mu_R - \mu_L)/(S_R^2 + S_L^2)^{1/2}$

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where iR, 'L are the means and SR, SL the standard deviations of the resistance and load distributions respectively. By use of variables reduced to standard normalised space, Hasover and Lind"1 showed that the reliability index could be regarded as the distance from the origin to the failure surface plotted in the n-dimensional space of the failure equation. This is shown for two variables XI and XZ in Fig. 7. The value of (3 can then be estimated by iterative numerical techniques which start with the mean values of the variables satisfying the failure equation and an arbitrary value of (3 and then slide along the failure curve until the minimum value of (3 is found. The design point is the position at which the variables have their most probable values for failure. A key issue is that although the procedure is strictly applicable only to normal distributions, it is possible to transform other types of distribution to equivalent normal distributions with the same values of probability density function and cumulative density function at the design point, as shown by Rackwicz and Fiessler.I2

To apply these techniques it is necessary to have a failure equation for the mode of failure being considered, and data on the distributions of each of the variables involved. Limit state design is effected in practice by the use of partial safety factors in which separate factors are applied to each of the input variables, and the structure is designed to fail under the action of these additional factors. The factors are used to multiply up loading effects and to divide into resistance effects, the magnitude of these factors being decided by a calibration exercise using one of the higher level methods to estimate the probability of failure as discussed in the next section. Although partial safety factors are an inherent part of limit state design codes for structural engineering, including in European

codes, they have generally only been used for failure by yielding or buckling.

Fracture/plastic collapse

For reliability analysis applied to fracture and plastic collapse it is convenient to use the BS 7910/R6 failure assessment diagram"3 (Fig. 8) and associated failure equations. The failure margin can be written as

$$M = K_r K_{mat} - K_I$$

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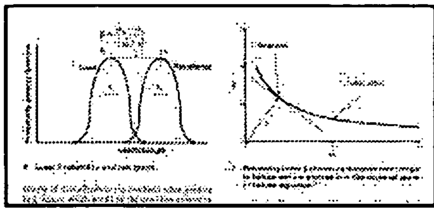
where K^sub I^ is the applied stress intensity factor given by K^sub I^= Y(omega)(pia)1/2, K^sub r^ is the permitted fracture ratio from the failure assessment diagram at the relevant value of the collapse ratio Lr, and K",$t is the relevant fracture toughness.



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6 Level 2 reliability analysis graph 7 Reliability index beta shown as distance from origin to failure surface plotted in n-dimensional space of failure equation12

The basic reliability analysis is carried out for a single defect with assumed uncertainties in estimates of its size, in which case the resulting probability of failure is per defect. This can be extended to a distribution of defects of different sizes, also with uncertainty in sizing, by discretising the distribution into a series of individual defects and combining the results for the whole distribution. This requires account to be taken of the total number of defects present or the defect incidence rate per unit length of weld and the length of welding present.

A number of computer programs have been developed in recent years, including one at UMIST called UMFRAP, to carry out calculations to determine the reliability index for fracture, plastic collapse, and fatigue assessments based on fracture mechanics prin

ciples. Examples of results from such calculations will be given in the next section.

Although partial safety factors have been used for some time in limit state design codes for yielding and buckling failure they have not been widely used in connection with fracture failure. An optional treatment was included in the 1991 version of PD 6493 and this has been updated for the 1999 issue of BS 7910. The basis of partial safety factors for fracture is shown in Fig. 9 on the same basis as the level 2 reliability analysis treatment of Fig. 6. Here the resistance effects are represented by K^sub r^K^sub mat^ (which includes both yield strength and fracture toughness) and the load effects by KI (which includes both stresses and crack size), in both cases with distributed values. For simple design or assessment purposes each of the variables in the load and resistance effects is represented by a single `characteristic' value. This may be an upper bound for load effects (say mean plus one or two standard deviations) and a lower bound for resistance effects (say mean minus one or two standard deviations), although mean values may also be used in some cases. Figure 9 shows the characteristic values of the load and resistance distributions as CL and CR respectively and also shows the design point as the intersection between the distributions where failure is most likely to occur. The overall partial factor on load effects yL can be defined as the ratio Lp/CL, where Lp is the value of the load effects at the design point, and the overall partial factor on resistance effects YR can be defined as the ratio CR/RD, where RD is the value of the resistance effects at the design point. (In fact Lp = RD, but they are described separately here for explanatory purposes). Partial safety factors on the individual variables which contribute to either load or resistance effects are then determined by a calibration procedure in which they are applied to characteristic values in the failure equation and tuned to give a required target probability of failure. Thus the values of partial safety factors for a given application depend on the target reliability required and the variability/scatter of the distributions of the variables concerned. This exercise has been carried out recently to determine partial safety factors for fracture/plastic collapse in BS 7910,13 for target probabilities of failure of 2-3 x 10-1, 10-3, 7x 10-5, and 10-5 and for different coefficients of variation of stress, defect size, fracture toughness, and yield strength. The target failure probability of 7 x 10-5 is that adopted as the basic requirement for design of steel structures to EuroCode 3 and hence the fracture requirements of BS 7910 have been derived to be entirely consistent with general structural codes.

Fatin ... Fatigue refers to the growth of cracks with number of cycles applied and hence introduces time into risk assessments. For fatigue treatments it is possible to consider either the S-N approach or the fracture mechanics approach based on the Paris Law

$$\frac{da}{dN} = C(\Delta K)^m$$

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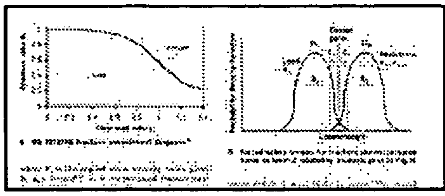
In the reliability approach, each of the variables or `constants' in the Paris Law can be regarded as having a distribution. Thus the initial defect size distribution grows to a new distribution at any time after application of fatigue damage. After any specified amount of damage, the probability of failure by plastic collapse or fracture can be estimated by using the instantaneous defect size distribution as an input to the analysis discussed in the previous section.



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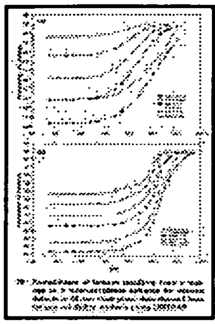
8 BS 7910/R6 fracture assessment diagram'3 9 Partial safety factors for fracture shown on same basis as level 2 reliability analysis plot in Fig. 6

The UMIST program UMFRAP has been used in a recent research project concerned with the reliability of flooded member detection (FMD) for offshore structures. The principle of FMD is the same as that of `leak before break' for pressure equipment. The bracing members of offshore platform structures are usually sealed before the platform is placed in the sea and hence should be air- and watertight. If cracking develops in service to the extent that it penetrates the wall thickness, it will be possible for water to get into the interior of the member. The presence of significant amounts of water inside these members can be detected by either radiographic or ultrasonic testing methods. This type of inspection can be carried out much more quickly than conventional nondestructive testing of all the welded joints and is effectively a screening method to confirm that major damage has not occurred. However, for FMD to be effective it is necessary to demonstrate that members can tolerate the presence of through thickness cracking without failure by fracture or plastic collapse. There must also be a sufficient margin between inspection times to ensure that cracks not causing leakage at the time of one inspection will not grow to failure before the next inspection. The full assessment of risk involves consideration of the consequences of failure of individual members and this depends on the degree of redundancy in the particular structure concerned. UMFRAP has been used to determine the change in probability for growth of cracks to cause leakage or failure by fracture/plastic collapse with fatigue damage S3N for a range of different thicknesses, defect sizes and shapes, and material properties. Examples of the results are shown in Fig. 10.

Data on statistical distributions of defects in welds in two major offshore platforms were collected by EQE Ltd from inspection records at the time of fabrication as part of this same project (note that all significant defects were repaired). The brace members were fabricated from `cans' with a series of circumferential butt welds (brace makeup welds), and they were welded into the structure by final circumferential butt welds to stubs at each end (brace closure welds). The closure welds had to be made by welding from the outside only and hence had somewhat more/ larger defects in their original distributions. The analyses were carried out both for the distributions derived from the inspection data and for postulated individual single defects of height 3, 6, 10, and 15 mm. Figure 10a shows the results for probability of leakage against S3N whilst Fig. lOb shows probability of fracture/plastic collapse against S3N for each of the defect cases. The standard design curves for butt welded joints for offshore structures are based on a relationship S3N=1 l4 x 1012 (N, mm units) and thus if a particular joint was designed right up to the limit, this value of S3N would correspond to the design life in years. If the actual design life of a joint is D years and the service life to a particular time is Y years, the amount of fatigue damage S3N at this time should be (Y/D) x 1.4 x 1012. The form of analysis leads to results in terms of probability of failure per defect. To obtain results for the probability of failure per member it is necessary to have available an estimate of the number of defects of the different types present from data on defect incidence rates, and this was also collected by EQE. The results are strictly conditional failure probabilities, since the calculations at any stage assume that failure has not occurred previously. The overall probability is then obtained by multiplying the conditional value obtained by the survival probability up to that stage. In practice this makes little difference until the conditional failure probabilities are sufficiently high that they would be unacceptable for practical safety requirements.

It can be seen from Fig. 10 that for the particular assumptions made for these cases, the probability of leakage is

higher than the probability of fracture for corresponding defects and amounts of fatigue damage. This particular conclusion is dependent on the thickness involved (which influences particularly the stage at which leakage occurs) and the fracture toughness. It can also be seen that the distributions of defects from the fabrication records give lower probabilities of failure per defect at any given level of fatigue damage than the individual defects. The absolute levels of probability of leakage or fracture from the defect distributions were very low until S3N values in excess of 1011 were reached. As expected the individual defects show increasing probability of both leakage and fracture with increasing size. In particular the larger defects show relatively high failure probability levels compared to normal acceptance targets. The overall conclusions from this work were that flooded member detection was a satisfactory screening method for finding cracks which had grown from rogue large defects escaping detection at the fabrication NDT stage, provided that the material toughness was high or the structure had sufficient redundancy to tolerate a failed member.



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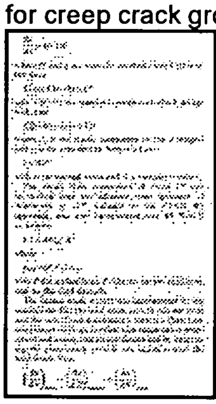
10 Probabilities of failures resulting from a leakage or h fracture/plastic collapse for various defects in 20 mm thick plate: data derived from fatigue reliability analysis using UMFRAP

Creep There appears to have been only limited application of quantitative risk analysis techniques in the field of creep failure. However in principle there would appear to be no reason why risk assessment methods should not be used provided sufficient data on material properties are available. Some work has been done by a group at Southwest Research Institutel covering both creep and fatigue interactions. The underlying failure equation adopted for creep crack growth was fracture mechanics based



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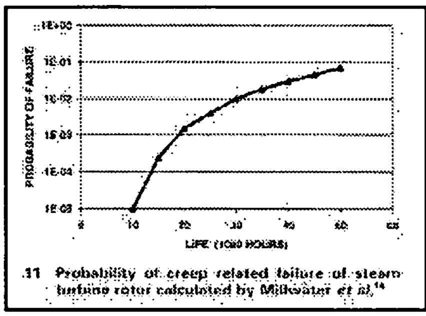
Total life is then obtained by integrating the combined crack growth equation to determine the number of cycles for the crack to grow from a given initial size to a limiting final size and calculating the time from the cyclic rate. Millwater et a1.14 include an example based on a probabilistic treatment of these equations for a rotor from a steam turbine. The approach they used is not given in detail but is described as an `advanced mean value' algorithm. The initial crack size was taken as 0'5 mm and failure was assumed to occur when the crack reached 85% of the section thickness. The results are shown in Fig. 11, from which it can be seen that the predicted probability of failure is becoming unacceptable for major engineering plant after some 20 000 hours. Clearly, with a design life of the order of 200 000 hours, regular inspection of the component in service would be necessary unless action could be taken to reduce the crack growth rate. By consideration of the sensitivity factors in the probabilistic approach it is possible to identify the factors contributing most to the problem. In this case the authors identified the variability in the material constant H as being the most significant, and further testing and data collection were recommended to try to reduce the uncertainty in this parameter.

The method described here has some similarities to the first order second moment approach described above for

fracture and fatigue. In principle the equations controlling creep and fatigue behaviour can be written as a failure equation and the first order second moment method used to predict probability of failure at any given time. Millwater et al. indicate that their method required about 200 creep crack growth analyses,14 whilst to compute a probability of failure by Monte Carlo simulation would require a minimum of 106 samples.

Corrosion Most of the applications of risk analysis to corrosion have been of the qualitative rather than the quantitative kind. There is increasing interest in this area and computerised risk assessment programs are beginning to be used. For example, organisations such as DNV, TWI Riskwise, Tischuk, and others have now produced such packages which are effectively knowledge based advisory systems. The difficulty with applying quantitative risk assessment methods to corrosion lies in the complexity of corrosion processes and the various different detailed mechanisms which can occur and their sensitivity to local conditions. For corrosion risk assessment, John et al.16 have identified the corrosion processes given in Table 2 which have to be considered. For qualitative assessments the rate of corrosion may be divided into categories, of which John et al. suggest four: extreme, high, medium, and negligible, with associated assessed corrosion rates of >0.5, 0.3-0-5, OM-0.3, and <0O1 mm/year respectively. The consequences of failure may also be divided into qualitative categories such as those given in Table 3.



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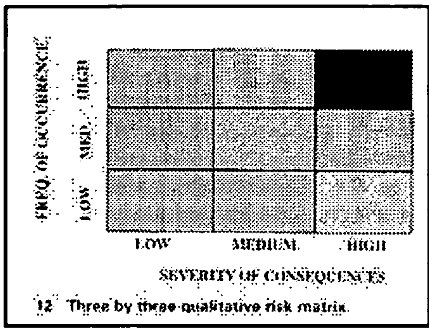
11 Probability of creep related failure of steam turbine rotor calculated by Millwater et al."

Qualitative risk assessments are often carried out using a matrix of the form shown in Fig. 12. Here, frequency of occurrence is shown on one axis and consequences on the other. Different squares of the matrix are given different colours to represent different degrees of risk. Figure 12 is divided into three categories for frequency and consequences but sometimes four or even five categories are used. Each component or structure is assessed for a particular mode of failure. Action is then decided depending on which square of the matrix locates the resulting combination of frequency and consequences. It should be noted that it may be decided to take different precautionary action when major consequences are combined with low frequency than when minor consequences are combined with high frequency. A more sophisticated version of this approach is shown in Fig. 13, where the matrix is five by five and the number of risk categories is four. 17

Most of the above approaches to risk assessment for corrosion are based on experience records or judgement to estimate a figure for the frequency of occurrence. Only limited work has been done to estimate probability of occurrence from probabilistic models of corrosion. Work on reliability based design for control of COZ corrosion was reported by Edwards et al.I8 using developments of equations by de Waard and Milliams.I9 Edwards et al. carried out full level 3 reliability analyses to give results for perceived probability of failure for two corrosion modes and five assumed cases of efficiency of inhibitor performance. The results were presented as probability of failure against life in years, but the scale for the probability of failure was linear from 0 to 0'7, which is much too insensitive for normal safety requirements.

Corrosion rates are often expressed in the literature in terms of mm/year, implying a linear rate for a particular material environment combination and corrosion mechanism. Extensive research has been carried out into corrosion rates for different mechanisms and the linear rate is a simplification for practical purposes. Laycock et al.20 analysed data on pitting corrosion to find distributions for pit depths and their rate of development. Their prime objective was to estimate the maximum pit depth since this would lead to leakage. They found that pit depths at any time followed an extreme value distribution and that mean pit depth typically followed the power law relation x=atb, where x is the mean pit depth, t is time, and a, b are constants depending on the material and environment. Typically b lies in the range 033-0-6, so that the assumption of linear growth with b =1 is likely to overestimate corrosion rates. This power law model can be used to predict the time for the first pit to penetrate the thickness, or average material loss through general corrosion. It is therefore possible to construct reliability models which would cover leakage or which could be used in conjunction with fracture/plastic collapse failure models taking account of

the reduction of cross-sectional area with time resulting from corrosion. It would appear however that so far the interaction with other modes of failure and the use of quantitative reliability analysis have not received much attention.



12 Three by three qualitative risk matrix

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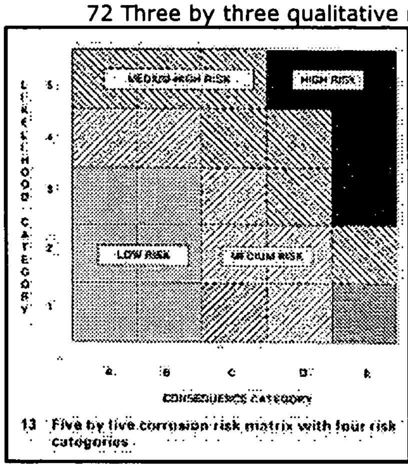
72 Three by three qualitative risk matrix



13 Five by five corrosion risk matrix with four risk categories

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13 Five by five corrosion risk matrix with four risk categories

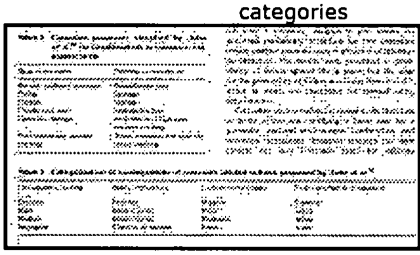

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Table 2 Table 3

Risk based inspection Risk assessment methods are becoming increasingly widely used as a basis for determining where and how often to inspect structures and components. This is happening more and more in the nuclear, offshore, and petrochemical industries and is being explored in the field of bridges. The direct application of this approach requires the subdivision of a structure into separate individual components followed by separate assessments of the probability of failure of each component by any relevant modes and assessment of the consequences of failure. The amount of data generated is considerable and the use of computer database management systems is becoming commonplace. The risks associated with the different components are then ranked using scoring schemes for probability and consequences, although these are usually judgement/experience based rather than using results of reliability analyses directly.

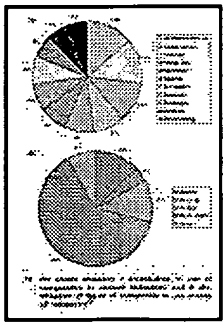
Recommendations for risk based inspection are being developed by the American Petroleum Institute for the petrochemical industry using both qualitative and quantitative approaches.zl The qualitative approach uses a five by five likelihood/consequence matrix. Users are required to complete a questionnaire which leads to a score for each answer and a cumulative result for likelihood and consequences. The position in the matrix determines the extent and frequency of inspection required. The quantitative approach is much more complicated with many more rating factors, but these are based on judgement and experience and do not appear to use reliability analysis explicitly. Application of risk analysis to new materials In principle it is possible to apply risk analysis techniques to any structural situation and any materials provided that failure equations exist for the relevant modes of failure and that there are sufficient data to define the material properties and their scatter/variability. Herein lie the difficulties,

however, and it would be true to say that complete dependence on risk assessment methods is better reserved for mature situations where there is confidence that the failure mechanisms and material variability are fully understood. Once the conditions governing failure are fully understood, to the extent that reliable design equations are available, and once sufficient reliable data are available, risk analysis can provide valuable insight into where benefits might be obtained without compromising safety. Risk analysis is not a substitute for good practice and experience. It can however provide a rational basis for decisions, provided it is soundly based. Two examples will now be given of the need for caution.

There is considerable interest in the use of high strength aluminium alloys for a range of transport vehicles, including cars, trains, and ships. These materials show favourable strength to weight ratios and can be produced in complex extruded shapes. Two particular problems require very careful attention by designers following this path with welded construction. First, the dynamic response of **vehicles** made of these materials may be such that vibrations may lead to fatigue crack growth problems. Thus it is essential to estimate the natural frequency of vibration of the structure or component and ensure that it is well removed from any potential exciting frequencies. Second, it is well known that the heat affected regions alongside welds in heat treated alloys may be significantly softer than the parent material and it is not uncommon to use weld metal which undermatches the parent material strength. Whilst the undermatching effect can be taken into account in conventional design either by use of a weld efficiency concept or by placing the welds at less highly stressed **locations**, a problem arises under extreme loading conditions. The presence of a localised weak band of material can lead to failure under extreme loading at this position without the benefits of more widespread plasticity and ductility to absorb energy before failure. It would be interesting to treat both of these problems on a **risk assessment** basis to quantify the relationship between probability of failure and material properties and loading conditions. There is also increasing use of plastics and composites in a wide range of industries. The distribution of use of composites among different industries is shown in Fig. 14a and the distribution of types of composite in Fig. 14b.22 The offshore industry is among the leaders in adopting use of composites, particularly for fire and blast protection. Again however it is important that sufficient research is done to understand the failure mechanisms and the material properties before these materials can be used with confidence in critical situations. It would be advantageous for this research to be done in an environment of risk assessment to obtain optimum utilisation.

A second example concerns the use of carbon fibre material for a high technology structural transport vehicle. The design involved tubular members connected by a member with low torsional stiffness. The stress concentration effect of the flexing of the walls of the tubular members due to torsion of the connecting member was not foreseen, although designers of offshore structures have been familiar with these effects in steel structures for the past twenty to thirty years. Cracking and fracture occurred in the tubular members. Risk assessment is of no value unless the appropriate structural behaviour and modes of failure are identified and correct failure equations applied. Conclusions The concept of risk as the product of the frequency of occurrence of an adverse event and the consequences of that event occurring is well established and is now widely used in industry. There is a significant difference between the risks which members of the general public are prepared to take with a free choice of their actions and the risk level which industry is expected to achieve to protect the public. Risk assessments can be carried out on a qualitative or on a quantitative basis. Both require judgement and experience and comparisons with observed events. There is considerable potential for developments in risk assessments using modelling analysis of different failure modes. This is well established in structural engineering in limit state design and has been developed on a research basis for fracture and fatigue failure. Quantitative risk assessment for creep and corrosion is still in its infancy. Risk based inspection is becoming well established in some industries, particularly the nuclear, offshore, and petrochemical industries.

With the development of new materials and new manufacturing/fabrication procedures there is much to be gained from adopting a risk assessment approach at an early stage to ensure that sufficient data are gathered to enable statistical distributions of properties to be assembled. It is also clear that it is important that all engineers and materials scientists should have a basic grounding in the principles of risk assessment and reliability analysis, since this will be a key basis for decisions in many areas of science and engineering.



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14 Pie charts showing a distribution of use of composites in various industries and b distribution of types of composite in use across all industries

[Footnote]
Notes and literature cited

[Footnote]
1. This paper was delivered at the AGM of The Institute of Materials on 6 June 2000 as the Fifth Finniston Lecture. The biennial Finniston Lecture series was founded in 1992 by The Institute of Materials in memory of Sir Monty Finniston, to mark his contribution to the materials and engineering communities; the previous lecturers have been Sir Alan Cottrell, Anthony Kelly, Stewart Miller, and Brian George.

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has been involved in assessments of structural integrity of a whole range of types of welded structures including buildings, bridges, pressure vessels, storage tanks, rotating machinery, ships, cranes, offshore structures, and pipelines, in research, as a consultant, on advisory committees, and for legal/arbitration cases. From 1983 to 1985 Professor Burdekin was a Vice-Principal of UMIST, with special responsibility for external affairs. He was particularly involved in relations with overseas universities, industry, and continuing education. In July 1987 Professor Burdekin was elected to the Fellowship of Engineering (now the Royal Academy of Engineering), from 1990 to 1993 he served as a member of the Engineering Council, and in March 1993 he was elected a Fellow of the Royal Society. He has been awarded the James Alfred Ewing Medal by the Institution of Civil Engineers, the Brooker Medal by the Welding Institute, the Arata Prize by the International Institute of Welding, and the Gold Medal of the Institution of Structural Engineers for his contributions to research and teaching.
